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HYDRAULICS OF THE FREE OVERFALL

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HYDRAULICS DIVISION

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HYDRAULICS OF THE FREE OVERFALL

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SYNOPSIS

The Free Overfall has so far been dealt with only in global terms and on certain more or less arbitrary assumptions as regards internal pressure distribution. In the present paper an account is given of a theoretical and experimental investigation of the problem on the basis of actual velocity and pressure distributions in the nappe. Variability of the bed-slope in the approach channel is taken into consideration.

INTRODUCTION

The fact is already known that the classical treatment of varied-flow in open channels is invalid for the region in the immediate neighborhood of a free overfall, owing to the departure from hydrostatic pressure conditions. Application of the ordinary varied-flow equation in that case leads to the following difficulties:

1) The theoretical surface slope at the terminal section is infinite, whereas, the slopes observed in practice are generally very mild.

2) The theoretical depth at the terminal section equals the critical depth for parallel flow ($\sqrt[3]{\frac{q^2}{g}}$) and is independent of the bed-slope of the channel. Observation shows, on the other hand, that the terminal depth is always appreciably smaller than the critical depth and that it changes sensibly with the bed-slope of the approach channel for the same discharge.

In addition to these difficulties, the equation fails altogether to account for drop-down flow in a sloping channel wherein the normal depth is smaller than the critical. Putting the equation in the form:

$$\frac{dY}{dx} = S_0 \frac{Y^3 - Y_n^3}{Y^3 - Y_c^3} \quad (1)$$

it will be noted that, for drop-down flow generally, $\frac{dY}{dx}$ is negative. If Y is everywhere less than Y_c , as prescribed, the denominator on the right hand side of (1) must be negative. Thus, in order that the whole quantity should have a negative sign, the numerator should be positive, i.e. Y should everywhere be greater than Y_n , which is contrary to the state of drop-down flow.

As regards the last remark, however, it may be noted that, in shooting flow, the velocity of flow is greater than the wave-velocity (\sqrt{gY}) and that any disturbance imposed on the flow at a given section will not travel far upstream.

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Thus, when the flow meets with an obstruction tending to increase the depth, no backwater will form and a sudden jump to the imposed depth will take place (hydraulic jump). On the other hand, when a decrease is imposed on the depth (as by giving the bed an abrupt drop) the drop-down effect will not extend to infinity upstream, as in the normal case of drop-down flow, and will be confined to a relatively short length in the channel, over which pressure conditions will be definitely non-hydrostatic.

Previous attempts to overcome the first two difficulties, when Y_n is greater than Y_c (or, to put it more generally, when the initial depth at the head of the channel is greater than the critical) are all based on the supposition that the critical depth is established at a certain distance upstream of the fall where pressure conditions are still hydrostatic. A relation between that depth and the terminal depth is then obtained either by treating the fall as a weir or by application of either the momentum or the energy equation, assuming the pressure at the terminal section to be atmospheric throughout. The snag in this supposition, however, is that the critical depth must be passed under definitely non-hydrostatic conditions; otherwise, the surface-slope at the respective section would be infinite.

In view of all these difficulties it would seem more convenient to deal with the flow in the neighbourhood of a free overfall on the basis of a modified varied-flow equation, wherein non-hydrostatic pressure conditions are taken into account. This would enable us to avoid arbitrary assumptions and to examine the similarity conditions by which the flow is governed on more rational lines.

Theoretical Investigation

To allow for non-hydrostatic pressure conditions, the varied-flow equation must be worked out from first principles.

Supposing the flow to be two dimensional, let $abcd$ (Fig. 1), be a stream-element of length δx and of unit width, comprised between two sections perpendicular to the bed.

The external forces acting on this element in a direction parallel to the bed are:

- 1) The pressure forces P_1, P_2 .
- 2) The gravity force component $G = \gamma Y \sin S_0 \delta x$.
- 3) The bed traction $T = \tau_0 \delta x$.

The resultant of these forces equals the time-rate of change of momentum through the element in the same direction:

$$\frac{d}{dx} \left[\int_0^Y p dy \right] \delta x - \gamma Y \sin S_0 \delta x + \tau_0 \delta x + \frac{d}{dx} \left[\rho \int_0^Y v^2 dy \right] \delta x = 0 \quad (2)$$

To simplify this equation we shall introduce a pressure correction factor, α , and a velocity (or momentum) correction factor, β , such that:

$$\alpha = \frac{2 \int_0^Y p dy}{\gamma Y^2} \quad (3)$$

$$\beta = \frac{\int_0^Y v^2 dy}{V^2 Y} \quad (4)$$

Further, we shall adopt as a similarity factor for frictional resistance the ratio of the boundary stress, τ_0 , to the kinetic energy per unit-volume (in terms of the mean velocity), $\frac{\rho V^2}{2}$

Hence,

$$f = \frac{2 \tau_0}{\rho V^2}$$

In the absence of any information on the behaviour of the coefficient of resistance in non-uniform flow, it will be assumed invariable for a given discharge.³ Making the necessary substitutions in (2) and dividing out by $\gamma Y \delta x$ we get:

$$\alpha \frac{dY}{dx} + \frac{Y}{2} \frac{d\alpha}{dx} - S_0 + \frac{q^2}{gY^3} \left(\frac{f}{2} + Y \frac{d\beta}{dx} \right) - \frac{q^2}{gY^3} \beta \frac{dY}{dx} = 0 \quad (6)$$

whence:

$$\frac{dY}{dx} = \frac{S_0 - \frac{Y}{2} \frac{d\alpha}{dx} - \frac{q^2}{gY^3} \left(\frac{f}{2} + Y \frac{d\beta}{dx} \right)}{\alpha - \beta \frac{q^2}{gY^3}} \quad (7)$$

This equation is not integrable and, without knowledge of the manner of variation of the quantities α , β , $\frac{d\alpha}{dx}$ and $\frac{d\beta}{dx}$ is of no use for determining the surface profile. Nevertheless, the said quantities must be subject to certain similarity conditions at the terminal section itself.

In this form, however, the equation serves to show clearly how the critical depth may be passed in non-uniform flow with a finite surface slope. When

$Y = Y_c$ the quantity $\frac{q^2}{gY^3} = 1$ Hence:

$$\left(\frac{dY}{dx} \right)_c = \frac{S_0 - \frac{Y}{2} \frac{d\alpha}{dx} - \left(\frac{f}{2} + Y_c \frac{d\beta}{dx} \right)}{\alpha - \beta} \quad (8)$$

In drop-down flow, the denominator $(\alpha - \beta)$ is always finite, since α must be less than unity and β is always greater than unity. Thus in no way can $\frac{dY}{dx}$ be infinite.

Furthermore, the drop-down effect with depths smaller than Y_c can be readily explained. In such a case, the quantity $\frac{q^2}{gY^3}$ will be greater than unity. The denominator on the right hand side of (7) will, therefore, be negative. In order that $\frac{dY}{dx}$ should remain negative, the numerator would have to be positive. Bearing in mind that both $\frac{d\alpha}{dx}$ and $\frac{d\beta}{dx}$ must be negative,⁴ there will be no impossibility in satisfying this condition, whatever the value of S_0 .

3. In the ordinary treatment of varied-flow, f is supposed to have the same value as in parallel flow.

4. This follows since, on the one hand, the deviation from hydrostatic conditions must increase in the direction of the fall and, on the other, velocity distribution tends to become more uniform as the fall is approached.

Experimental Investigation

The experimental work was carried out with two objects in view:

- i) To verify the revised varied-flow equation (7), and
- ii) To determine the similarity conditions for the flow properties at the terminal section.

The apparatus employed consisted mainly of a rectangular iron flume 0.50 m (1 ft. 7.7 in.) wide, 0.40 m. (1 ft. 3.8 in.) deep and 3.00 m. (9 ft. 10 in.) long, placed in a hydraulic circuit of a maximum capacity of 63 Lit. per Sec. (832.2 Gal. per Min.). The flume was hinged at the inlet end and supported on a jack at the exit end, so that it could be given different slopes ranging be-

tween $+\frac{1}{30}$ (downward) and $-\frac{1}{30}$ (upward). The terminal depth obtained at maximum discharge was of the order of 8 cms. (3.15 in.) or about one-fifth of the flume width. Thus the flow could be treated as very nearly two-dimensional.

A special device (Figs. 2 & 3) was employed to enable a pressure and velocity survey being made of the stream for some distance on either side of the terminal section. This consists of an ordinary Pitot-tube for observing the dynamic head ($\frac{p}{\gamma} + \frac{v^2}{2g}$) and a "Direction-Vane" for determining the direction of flow and the static head $\frac{p}{\gamma}$. The latter unit consists of a thin strip of phosphor bronze 30 mms. (.118 in) long, 10 mms. (.393 in) wide and 0.2 mms. (.008 in) thick, to which are soldered two short lengths of fine copper tubing, one on each face, and 10 mms. (.393 in) apart. The tube ends are cut obliquely 2 mms. (.08 in) short of the forward edge of the vane and sealed up. A 0.6 mms. (.024 in) hole is drilled through each face of the vane to communicate with the tube on the opposite side. Both Pitot-tube and Direction-Vane are mounted on a rotatable shaft, with a pointer on a graduated arc to measure the angle through which the shaft is turned. The mounting is so arranged that the position in space of the Pitot-tube and direction-vane orifices does not change with rotation. The supporting frame is carried on an extension to the flume in such a way that the point of observation can be set at known depths above (or below) bed level and at known distances on either side of the terminal section. The apparatus is inserted into the stream from the downstream end. Obviously, the direction-vane will lie in the direction of flow when the pressures registered for both faces are the same. When in that position, the pressure indicated, relatively to the point of observation, will be the static pressure and the velocity head can be obtained by subtracting the balanced static head from the dynamic head registered simultaneously by the Pitot-tube. Special tests showed that there was no interference between the vane and Pitot-tube, and that the slight disturbance caused by the supporting frame did affect the observations. Calibration tests also showed that the vane and Pitot-tube coefficients were both equal to unity. In using the apparatus, however, it was found necessary to wipe the forward edge and the two faces of the vane with a brush immediately before each reading, so as to remove any accumulation of dirt or air bubbles which would put the vane out of action. Further, it was found useful to flush the tube system with water from a high level tank from time to time, to drive out air bubbles.

Pressure and velocity surveys were carried out for several discharges and several positive and negative bed slopes.

To give some idea of the relative order of magnitude of the quantities appearing in Equ. (7), the following figures are quoted for the case of a discharge of 40 Lit. per Sec. (528.4 Gal. per Min.), with a horizontal bed:

$$\begin{array}{lll}
 Y_t = 6.16 \text{ cms. (2.42 in.)} & \alpha = 0.14 & Y \frac{d\beta}{dx} = -.005 \\
 \frac{q^2}{9Y^3} = 2.77 & \frac{Y}{2} \frac{d\alpha}{dx} = -.674 & f = .018 \\
 \left(\frac{dY}{dx}\right)_t = -.25 & \beta = 1.015 &
 \end{array}$$

The following are the principal conclusions arrived at:

a) The terminal depth is a function of both the discharge and the bed slope. The relation may be expressed in the form:

$$Y_t = k \sqrt[3]{\frac{q^2}{g}} \quad (9)$$

where k varies with S_0 as indicated in Fig. 4.

This relation may be defined in another way by saying that, for a given bed slope, there is a definite value of the Froude Number at the terminal section which is independent of the discharge. Fig. 5 shows the derived relationship between S_0 and the Froude Number $\sqrt{\frac{q^2}{9Y^3}}$. For a horizontal bed $F_t = 1.66$ and for a downward slope of 1 in 20, it rises to 3.24.

This result confirms the suggestion put forward by Rouse in 1936³, that the free overfall provides an easy means of measuring the discharge. It further shows that that suggestion is valid for sloping as well as for horizontal channels. From (9) it readily follows that

$$q = k^{-\frac{3}{2}} \sqrt{g} Y_t^{\frac{3}{2}} \quad (10)$$

Noting that $F_t = \sqrt{\frac{q^2}{9Y_t^3}}$ it will be seen that the coefficient ($k^{-\frac{3}{2}}$) has precisely the same value as F_t , which varies with S_0 as shown in Fig. 5.

b) The terminal surface slope is a function of the bed-slope only and bears to it a relation of similar character to that connecting k with S_0 (Fig. 6).

A striking feature of the two curves shown in Figs. (4) and (6) is that in both there is an inflection at the point where S_0 has the same value as the coefficient of resistance. The significance of this feature remains to be investigated.

The most interesting feature of the hydraulic survey was the distribution of pressure in the region of the fall. In all the cases tried, sub-atmospheric pressures were indicated, beginning near the free surface upstream of the fall and spreading out until they covered the entire section in the free jet. For a horizontal bed, the pressure distributions recorded were as shown in Fig. 7. With a bed slope of +.0275 (downward) and a discharge of 28.3 Lit. per Sec. (374 Gal. per Min.), the pressure at the terminal section was wholly sub-atmospheric and the value of the pressure correction factor was -.136. These results have been checked by repeating the observations several times.

Significance of Sub-Atmospheric Pressures in the Nappe

The existence of sub-atmospheric pressures in the nappe and the free jet may appear, at first sight, somewhat puzzling. It is to be noted, however, that the case in question is one of dynamic and not static equilibrium, and there is no reason, from the dynamic point of view, why departure from hydrostatic conditions should stop at zero (or atmospheric) value. Physically, the change-over to sub-atmospheric values, may be restrained, to some extent, by the liberation of air carried by the water in solution or in suspension, but even then,

such restraint cannot prevent lowering of pressure entirely as the water is continuously renovated.

For a detailed analysis of the dynamical conditions governing motion, in this case, we should, obviously, take into account tangential or internal friction stresses as well as the variability of pressure with direction, which follows on admission of these stresses. Using the natural system of co-ordinates (streamlines and orthogonals) the dynamical equations are expressible thus: For a streamline:

$$\frac{p_s - p_n}{r_s} - \frac{dp}{ds} + \frac{dT}{dn} + \frac{2T}{r_s} + \gamma \sin \sigma \frac{v^2}{r_s} = 0 \quad (11)$$

and for an orthogonal:

$$\frac{p_s - p_n}{r_s} - \frac{dp}{dn} + \frac{dT}{ds} - \frac{2T}{r_s} - \gamma \cos \sigma \frac{v^2}{r_s} = 0 \quad (12)$$

where S = Distance measured along a streamline.

n = " " (upwards) along an orthogonal.

T = Local tangential stress.

σ = Slope of tangent to streamline.

r_s = Radius of curvature of orthogonal

r_f = " " " " streamline.

The last equation only is of interest to us at present. In the absence of knowledge about the distribution of tangential stresses within the stream, it is not possible to make use of that equation in full. Since, however, the tangential stress at the free surface is zero (neglecting air resistance), the first, third and fourth terms of that equation vanish. Hence, for the surface line we may write:

$$\frac{dp}{dn} = \rho \frac{v^2}{r_f} - \gamma \cos \sigma \quad (13)$$

This equation provides us with a clue as to the possibility of the pressure falling below atmospheric immediately below the surface. Noting the n is measured positively upwards, a positive value of $\frac{dp}{dn}$ would mean a negative change in the pressure. Thus, the answer to the question whether sub-atmospheric pressures in the nappe may or may not be possible depends on whether the quantity $\rho \frac{v^2}{r_f}$ may or may not be greater than $\gamma \cos \sigma$.

Owing to the difficulty of measuring r_f accurately, it has not been possible to make a definite quantitative check on (13). The case, in fact, is one involving the determination of small differences between large quantities, which is known to be extremely difficult. The measurements obtained, however, show that a negative pressure gradient from the surface downwards is quite probable.

REFERENCES

1. Discharge Characteristics of the Free Overfall. Dr. H. Rouse, "Civil Engineering" for April 1936.

2. Effects of Distortion in Hydraulic Models. Prof. M. P. O'Brien, "Engineering News Record" for September 15, 1932.
3. Dodge and Thompson's Fluid Mechanics, Chap. X, Art. 127.

NOTATION

The following letter symbols adopted for use in this paper, conform essentially with American standard Letter Symbols for Hydraulics (ASA - Z10.2 - 1942).

v - Velocity parallel to the bed at a point.

V - Mean velocity through a section perpendicular to the bed.

y - Height of point perpendicular to the bed.

Y - Stream depth perpendicular to the bed.

q - Discharge per unit width of channel.

Y_n - Normal or uniform-flow depth.

Y_c - Critical Depth = $\sqrt[3]{\frac{q^2}{g}}$

x - Distance along the bed.

S_o - Bed slope.

γ - Specific weight of water = ρg

τ_o - Tractive stress on bed.

f - Coefficient of Resistance for channel = $\frac{2 \tau_o}{\rho V^2}$.

α - Pressure correction factor (Equ. 6).

β - Velocity or momentum correction factor (Equ. 7).

F - Froude Number = $\sqrt{\frac{q^2}{gY^3}} = \frac{V}{\sqrt{gY}}$.

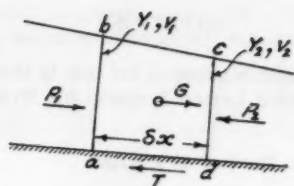


Fig. (1)

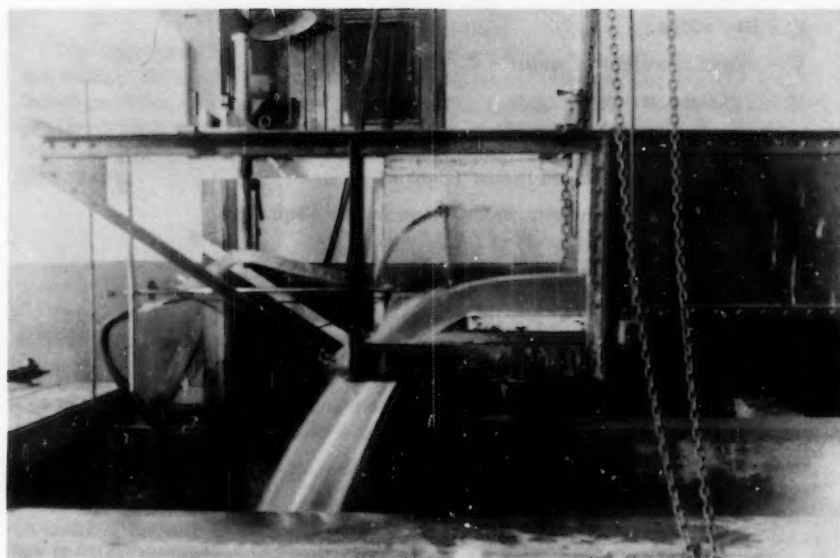


Fig. 2 - Measuring Device mounted in position.

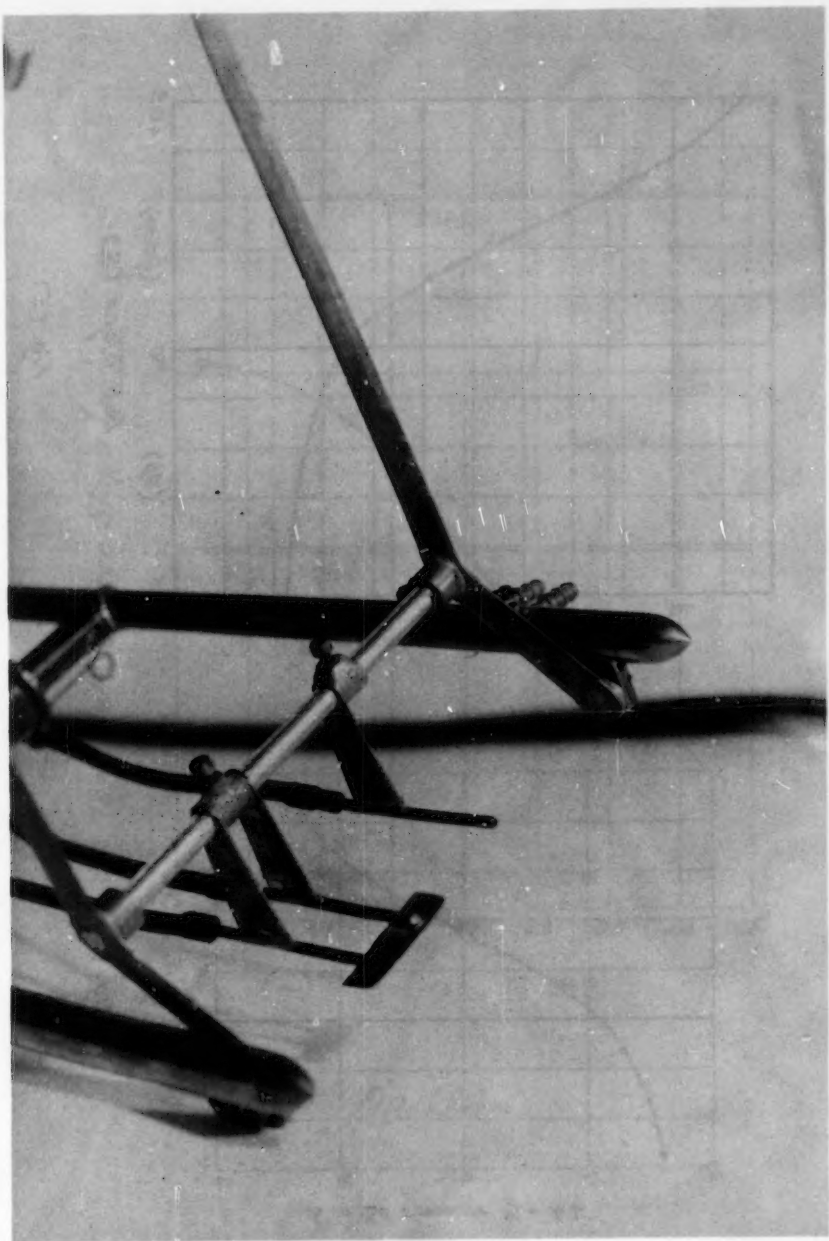


Fig. 3 - Direction-Vane and Pitot Tube.

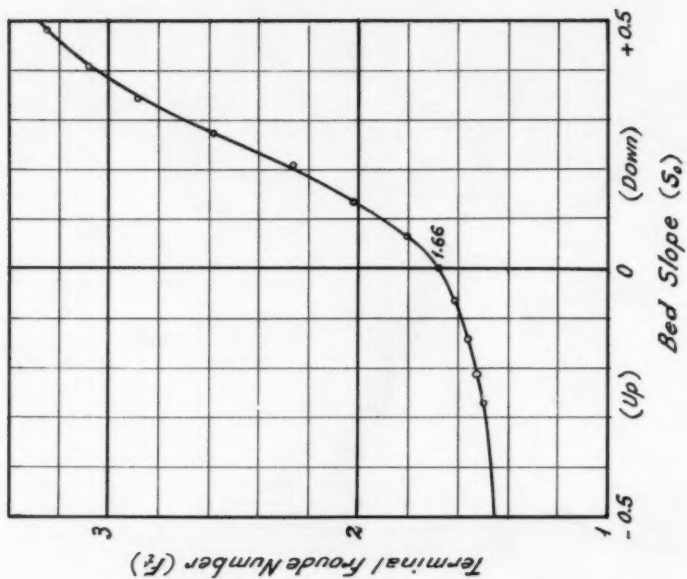


Fig. (5)

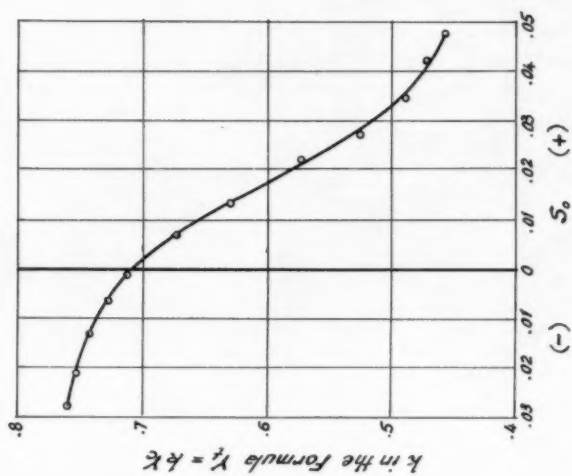


Fig. (4)

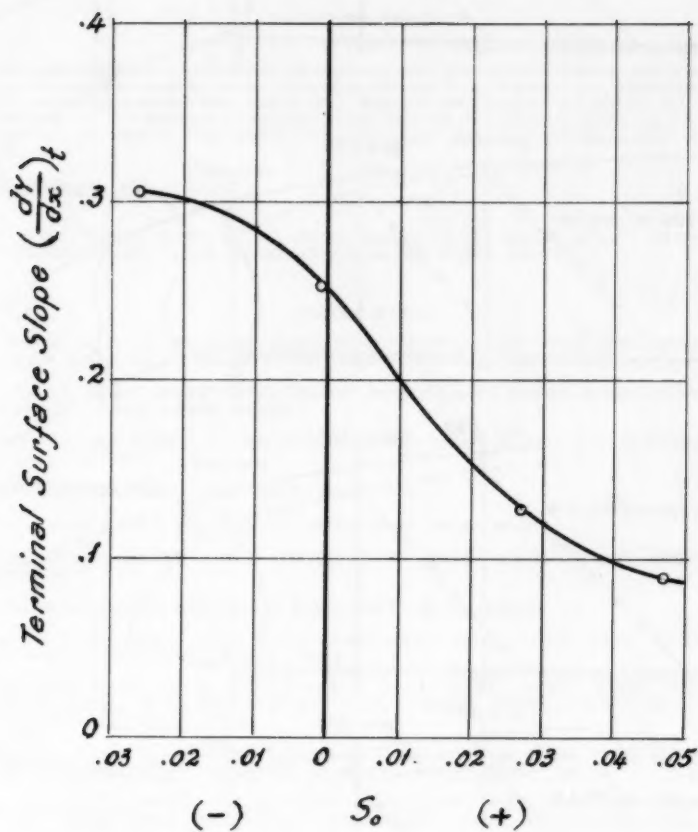


Fig. (6)

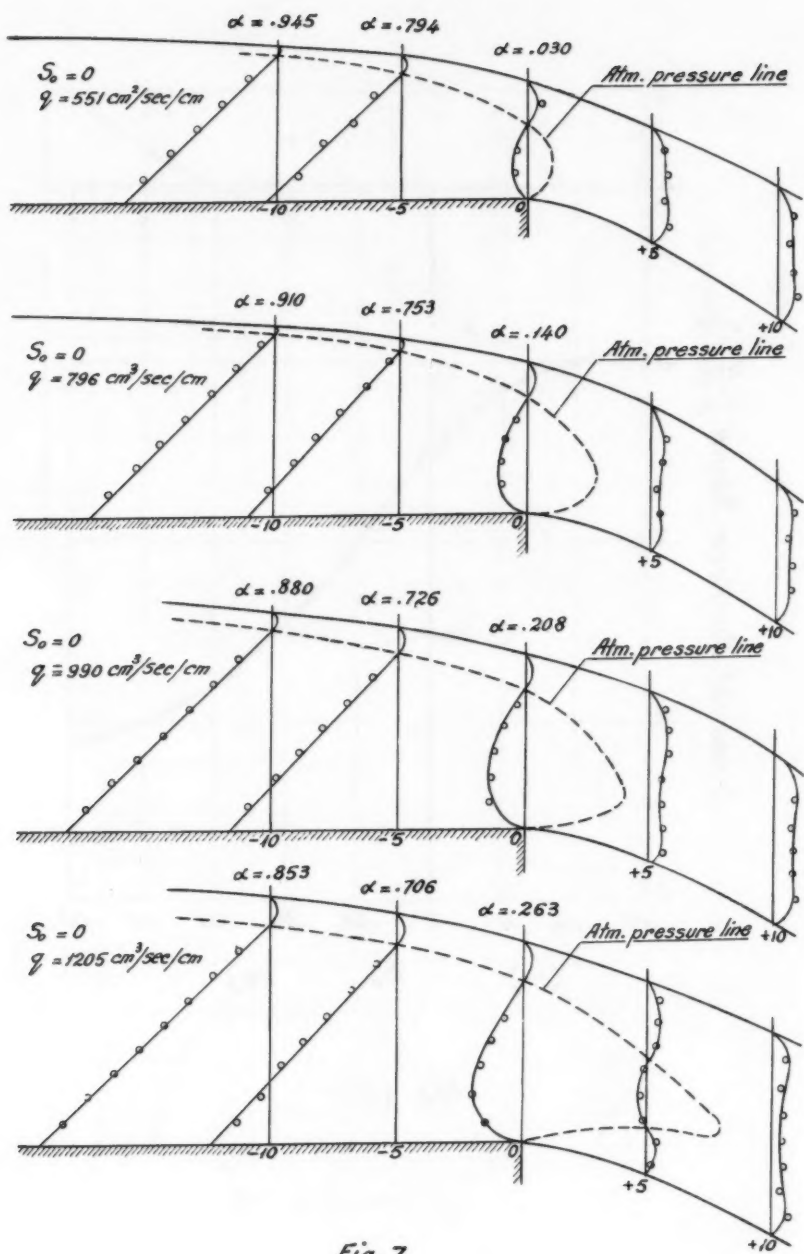


Fig. 7

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c. Discussion of several papers, grouped by Divisions.

d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.

e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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